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# RESEARCH MEMORANDUM

## A NOTE ON THE DRAG DUE TO LIFT OF DELTA WINGS AT MACH NUMBERS UP TO 2.0

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON
April 9, 1953

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## SUMMARY

In order to indicate the effects of Reynolds number and other variables on the drag due to lift of delta wings for Mach numbers up to 2.0, the results of several investigations of wing-body combinations having delta wings with aspect ratios from 2 to 4 have been assembled for comparison and brief analysis.

The effects of Reynolds number, leading-edge radius, and thickness ratio could generally be correlated with Reynolds number based on the leading-edge radius as a parameter. The effects of leading-edge Reynolds number on drag due to lift were large at Mach numbers less than 0.25. However, with increases in Mach number, the effects decreased and were almost negligible at a Mach number of 2.0. The effects of aspect ratio were large, as would be expected.

It was indicated at least for subsonic speeds that improvement in the drag due to lift might be obtained from wing modifications designed to inhibit flow separation at the wing tip.

## INTRODUCTION

Low-speed investigations of delta wings have indicated that Reynolds number variations have large effects on drag due to lift (see ref. 1, for example). Because of the interest in the delta wing for transonic and supersonic flight, it is important to investigate whether the same scale effect exists at higher speeds. Accordingly the readily available experimental investigations of delta wings for Mach numbers up to 2.0 have been reviewed and analyzed with special reference to the drag due to lift. The results of this analysis are given in the present paper. Effects of Reynolds number, aspect ratio, thickness ratio, and leading-edge radius are presented for delta wings in combination with bodies.

The drag increment associated with trimming the typical tailless airplane configuration is also discussed, and possible modifications for reducing the drag due to lift are suggested.

## SYMBOLS

| | |
|---|---|
| $C_D$ | drag coefficient based on total wing area |
| $C_L$ | lift coefficient based on total wing area |
| $\frac{dC_D}{dC_L^2}$ | drag-due-to-lift factor averaged up to $C_L = 0.3$ |
| $M$ | Mach number |
| $A$ | aspect ratio |
| $R_{L.E.}$ | Reynolds number based on leading-edge radius |
| $R_{\bar{c}}$ | Reynolds number based on wing mean aerodynamic chord |
| $r_{L.E.}$ | leading-edge radius in percent chord (measured streamwise) |
| $\bar{c}$ | mean aerodynamic chord |
| $t/c$ | wing thickness ratio, fraction of chord |

## SOURCES AND EVALUATION OF DATA

Most of the data presented herein were obtained from tests of wing-body combinations on sting supports in wind tunnels or as free-flight rocket models. Some of the configurations, however, included a vertical fin, and for Mach numbers below 0.25 some wing-alone data have been used in order to extend the range of $R_{L.E.}$ above $21 \times 10^3$. Most of the data have been published (refs. 2 to 18), the remainder being unpublished data from the Langley 8-foot transonic tunnel, the 4- by 4-foot supersonic pressure tunnel, and the low-turbulence pressure tunnel. A summary of the data sources including the Mach number range, range of Reynolds number based on the wing mean aerodynamic chord, airfoil section, aspect ratio, leading-edge radius in percent chord, and reference number is given in table I.

Where a usable lift-drag polar was available, the value of the drag-due-to-lift factor $\frac{dC_D}{dC_L{}^2}$ was taken as the slope of the straight line through the point at $C_L = 0$ that best approximates the plot of $C_D$ against $C_L{}^2$ in the lift-coefficient range from 0 to 0.3. When the polars were not available, values of $\frac{dC_D}{dC_L{}^2}$ as presented in the reference were used.

It is possible that at transonic Mach numbers the drag due to lift may be significantly affected by body size and shape and by the location of the wing on the body (ref. 19). For the configurations presented herein, however, the body characteristics at transonic speeds are considered sufficiently similar to allow the present comparisons. At very low speeds the results of reference 1 indicate that addition of a body has little effect on the drag due to lift, and therefore wing-alone and wing-body results are probably comparable at Mach numbers below 0.25.

## DISCUSSION

### Effects of Reynolds Number and Leading-Edge Radius

Values of the drag-due-to-lift factor $\frac{dC_D}{dC_L{}^2}$ for several delta-wing configurations with aspect ratios from 2.0 to 2.3 are plotted in figure 1 against Reynolds number based on the leading-edge radius and free-stream velocity. The wings had various symmetrical airfoil sections and leading-edge radii and, except for the low-speed data, were generally less than 6 percent thick (table I and refs. 2 to 16). A scale of Reynolds number based on mean aerodynamic chord with a typical leading-edge radius of 0.2-percent chord (representing an NACA 63A005 airfoil section, for example) is also shown in order that the reader may be oriented to values with which he is more familiar.

It is significant that data at any chosen Mach number but from different sources fall on the same curve with relatively small scatter. Apparently the leading-edge Reynolds number is the most significant single parameter in this correlation of plane symmetrical delta wings. The major differences in leading-edge Reynolds number shown are due to differences in $R_{\bar{c}}$.

Large decreases in $\frac{dC_D}{dC_L^2}$ are indicated with increases in Reynolds number at very low speeds. It will be noted at high Reynolds numbers that the drag due to lift at these speeds approaches the theoretical value for full leading-edge suction as calculated by the Weissinger method. (The data used, however, are for wing thickness ratios as high as approximately 12 percent, which are not considered favorable for high-speed flight.) With increases in Mach number, the effects of Reynolds number on $\frac{dC_D}{dC_L^2}$ decrease and become almost negligible at a Mach number of 2.0. At transonic and supersonic speeds, compressibility effects determine the flow characteristics over the wing leading edge and variations with Reynolds number would be expected to be small.

At supersonic speeds, the data indicate that the drag due to lift is much higher than for low speeds. Part of this difference is accounted for by the effects of increasing Mach number on the theoretical (full leading-edge suction) value (refs. 20 and 21) as shown in figure 1. The data, however, also indicate a greater departure from the theoretical values at supersonic speeds than at low speeds.

## Effects of Mach Number and Aspect Ratio

The variation with Mach number of the drag-due-to-lift factor $\frac{dC_D}{dC_L^2}$ is presented in figure 2 for aspect ratios from 2 to 4. For these aspect ratios, the drag due to lift decreases with an increase in Mach number from 0.60 to approximately 1 and increases rapidly at supersonic Mach numbers. For thin wings with relatively sharp leading edges, the leading-edge suction is largely lost and the variation of $\frac{dC_D}{dC_L^2}$ with Mach number is approximately the same as the variation obtained using the reciprocal of the experimental lift-curve slope.

As would be expected, marked reductions in the drag-due-to-lift factor result from an increase in aspect ratio. For the configurations employing wings of aspect ratios 3 and 4, reductions in $\frac{dC_D}{dC_L^2}$ amount to about 28 and 40 percent, respectively, at subsonic speeds and 20 and 30 percent, respectively, at supersonic speeds as compared with the values for the aspect-ratio-2 configuration.

## Effects of Thickness Ratio

Some effects of thickness ratio on the drag due to lift of delta wings of aspect ratio 2.0 and 2.2 are shown in figure 3. The data follow the trends shown in figure 1. The decrease in $\frac{dC_D}{dC_L{}^2}$ with increasing thickness ratio was expected because the increase in leading-edge radius causes an increase in leading-edge Reynolds number.

It is notable that the 8-percent-thick wing exhibits an increase in drag due to lift with increasing Mach number at subsonic speeds, a trend opposite to that shown for the thinner wings, indicating again that at high subsonic speeds, compressibility effects rather than Reynolds number fix flow over the leading edge.

## Effects of Wing Modifications

Data presented in references 22 and 23 indicate that wing modifications such as twist and camber offer reductions in the drag due to lift for delta wings when the Mach number perpendicular to the leading edge is less than approximately 0.70. Also, a recent investigation (unpublished data) indicates that chordwise fences are effective at transonic speeds. The data shown in figure 4 were obtained from model tests of an airplane configuration having a delta wing with an aspect ratio of 2.2 and NACA 0004-65 airfoil sections. The test Reynolds number based on the leading-edge radius was approximately 8,000 $\left(R_{\bar{c}} = 4.5 \times 10^6\right)$.

The addition of chordwise fences extending from the leading edge to 80 percent of the chord at the 65-percent wing semispan station decreases the drag due to lift approximately 20 percent at Mach numbers from 0.6 to 0.95. At higher Mach numbers the beneficial effects decrease, and at a Mach number of 2.0 no gain is indicated. The failure of the fences to improve $\frac{dC_D}{dC_L{}^2}$ at a Mach number of 2.0 might be expected since the effect of fences is similar to an increase in Reynolds number and the effects of Reynolds number were shown in figure 1 to be greatly reduced at a Mach number of 2.0. The increment in drag due to lift between the lowest experimental value of $\frac{dC_D}{dC_L{}^2}$ and the theoretical value remained essentially constant for all the Mach numbers tested.

Effects of Trimming a Tailless Configuration

Longitudinal control of a delta-wing airplane by trailing-edge elevons may result in a substantial penalty in drag due to lift for trim conditions because the effective tail length is relatively short and large control surfaces and deflections may be required to produce the longitudinal balancing moments.

It is indicated in reference 24 that trimming a wing-body combination with a delta wing of aspect ratio 2 $\left(R_{\bar{c}} = 3 \times 10^6\right)$ increased $\frac{dC_D}{dC_L{}^2}$ by from 18 percent to 55 percent over a Mach number range from 0.6 to 1.70. The elevon area was approximately 20 percent of the total wing area and the static margin varied from 5 to 15 percent of the mean aerodynamic chord. For larger static margins the effects of trimming would be expected to be more severe. The large increase in the drag-due-to-lift increment for trim with increasing Mach number is due to a combination of increased longitudinal stability and decreased control effectiveness.

Effects of elevon deflection on minimum drag and drag due to lift for a delta-wing configuration are presented and discussed in some detail in reference 6.

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TABLE I.- SUMMARY OF DATA SOURCES

| Aspect ratio | Airfoil section | M range | $R_{\bar{c}}$ range | $r_{L.E.}$ | Reference |
|---|---|---|---|---|---|
| 2.0 | 0003-63 | 0.60-1.7 | $5.0 \times 10^6$ | 0.10 | 3 |
| 2.0 | 0005-63 | .24-1.7 | $3.0 \times 10^6$ | .28 | 4 |
| 2.0 | 0008-63 | .24-1.7 | $3.0 \times 10^6$ | .70 | 5 |
| 2.0 | 5 percent thick double wedge | .18-.95 | $5.3 \times 10^6$ | .25 | 7 |
| 2.0 | 5 percent thick double wedge | .5-1.5 | $.67\text{-}.85 \times 10^6$ | $\approx .05$ | 9 |
| 2.0 | 5 percent thick double wedge | .5-1.5 | $.67\text{-}.85 \times 10^6$ | $\approx .05$ | 10 |
| 2.0 | 0005 (Mod.) | .13 | $15.3 \times 10^6$ | .28 | 16 |
| 2.2 | 0004-65 (Mod.) | 1.22-2.16 | $\approx 1.0 \times 10^6$ | .18 | 2 |
| 2.2 | 0004-65 (Mod.) | .70-.94 | $1.5\text{-}3.5 \times 10^6$ | .18 | 8 |
| 2.2 | 0004-65 (Mod.) | .60-2.01 | $3.8\text{-}7.3 \times 10^6$ | .18 | Unpublished |
| 2.31 | $65_{(06)}$A006.5 | .75-1.7 | $11.0\text{-}24.0 \times 10^6$ | .274 | 6 |
| 2.31 | 65A003 | .12 | $2.77 \times 10^6$ | .057 | 11 |
| 2.31 | Flat plate | .13 | $1.6 \times 10^6$ | 1.2 | 12 |
| 2.31 | 0012 | .13 | $1.62 \times 10^6$ | 1.58 | 12 |
| 2.31 | Flat plate | .13-.27 | $1.5\text{-}3.0 \times 10^6$ | 1.24 | 13 |
| 2.31 | 65-010 | <.25 | $6.0\text{-}9.7 \times 10^6$ | .687 | 14 |
| 2.31 | 65-010 | .07 | $6.0 \times 10^6$ | .687 | 15 |
| 2.31 | 65A002 | .15-1.125 | $2.6\text{-}3.5 \times 10^6$ | .025 | Unpublished |
| 2.31 | 65A006 | .15-.60 | $3.0\text{-}9.3 \times 10^6$ | .229 | Unpublished |
| 3.0 | 0003-63 | .60-1.7 | $4.8 \times 10^6$ | .10 | 17 |
| 4.0 | 3 percent thick biconvex (mod.) | .60-1.7 | $4.15 \times 10^6$ | .045 | 18 |

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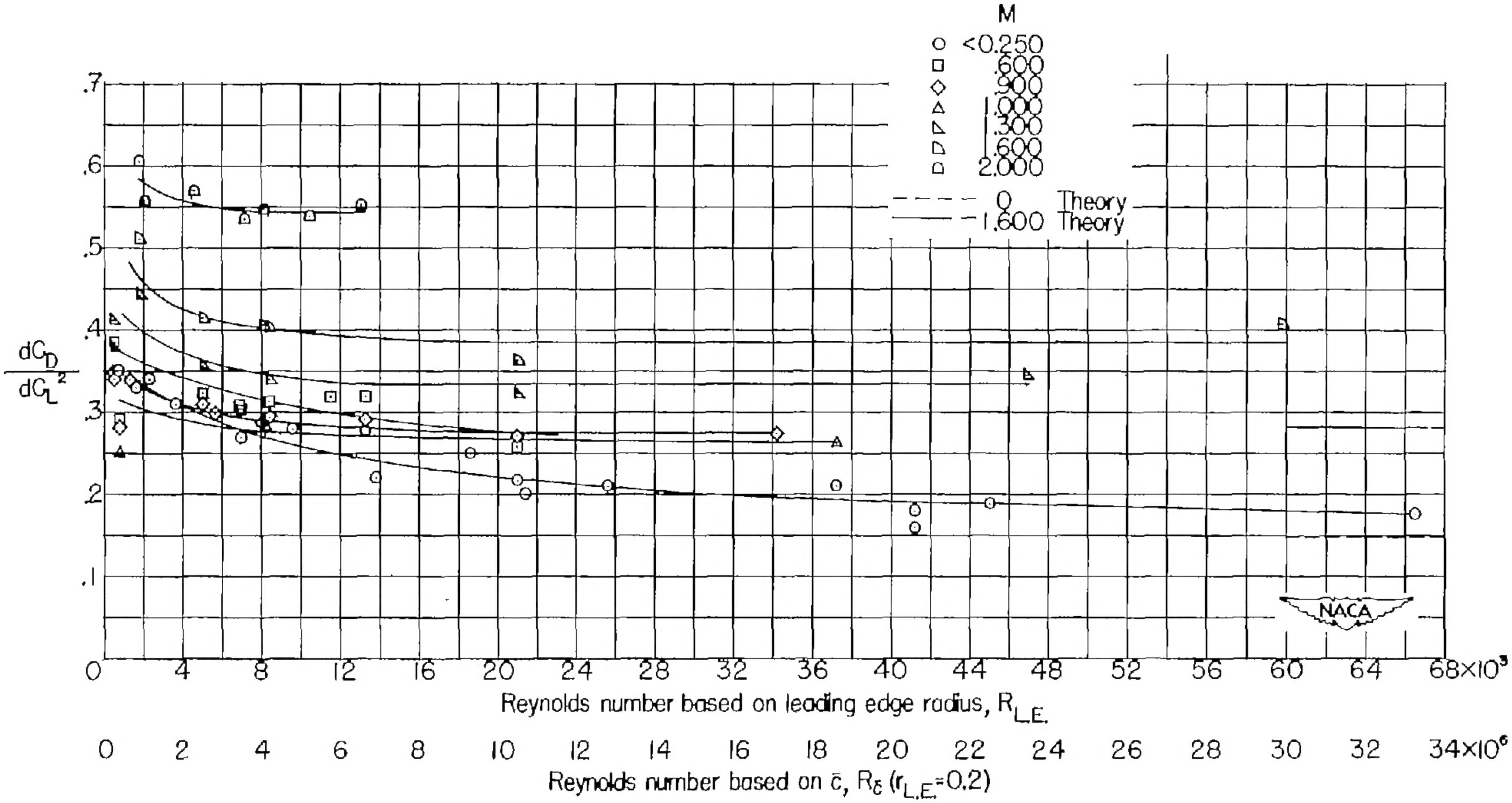


Figure 1.- Variation of drag-due-to-lift factor $\frac{dC_D}{dC_L^2}$ with Reynolds number based on the leading-edge radius for several configurations having delta wings with aspect ratios from 2.0 to 2.3. $\left(\frac{dC_D}{dC_L^2}\right.$ averaged to $\left.C_L = 0.3.\right)$

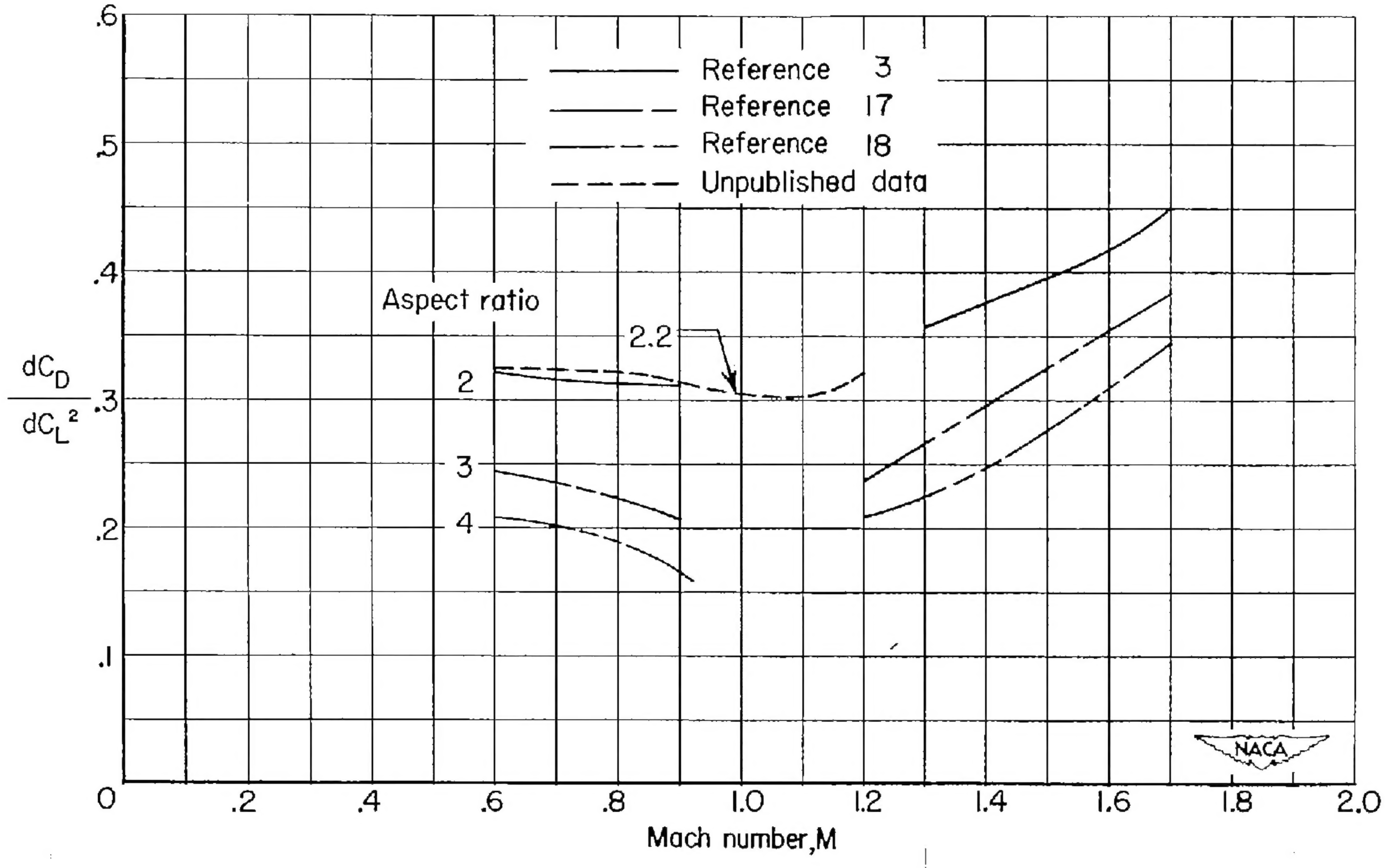


Figure 2.- Variation of drag-due-to-lift factor $\frac{dC_D}{dC_L^2}$ with Mach number for wing-body combinations having delta wings with aspect ratios from 2.0 to 4.0. $R_{\bar{c}} \approx 5 \times 10^6$; $t/c \approx 0.03$. $\left(\frac{dC_D}{dC_L^2}\right.$ averaged to $\left.C_L = 0.3.\right)$

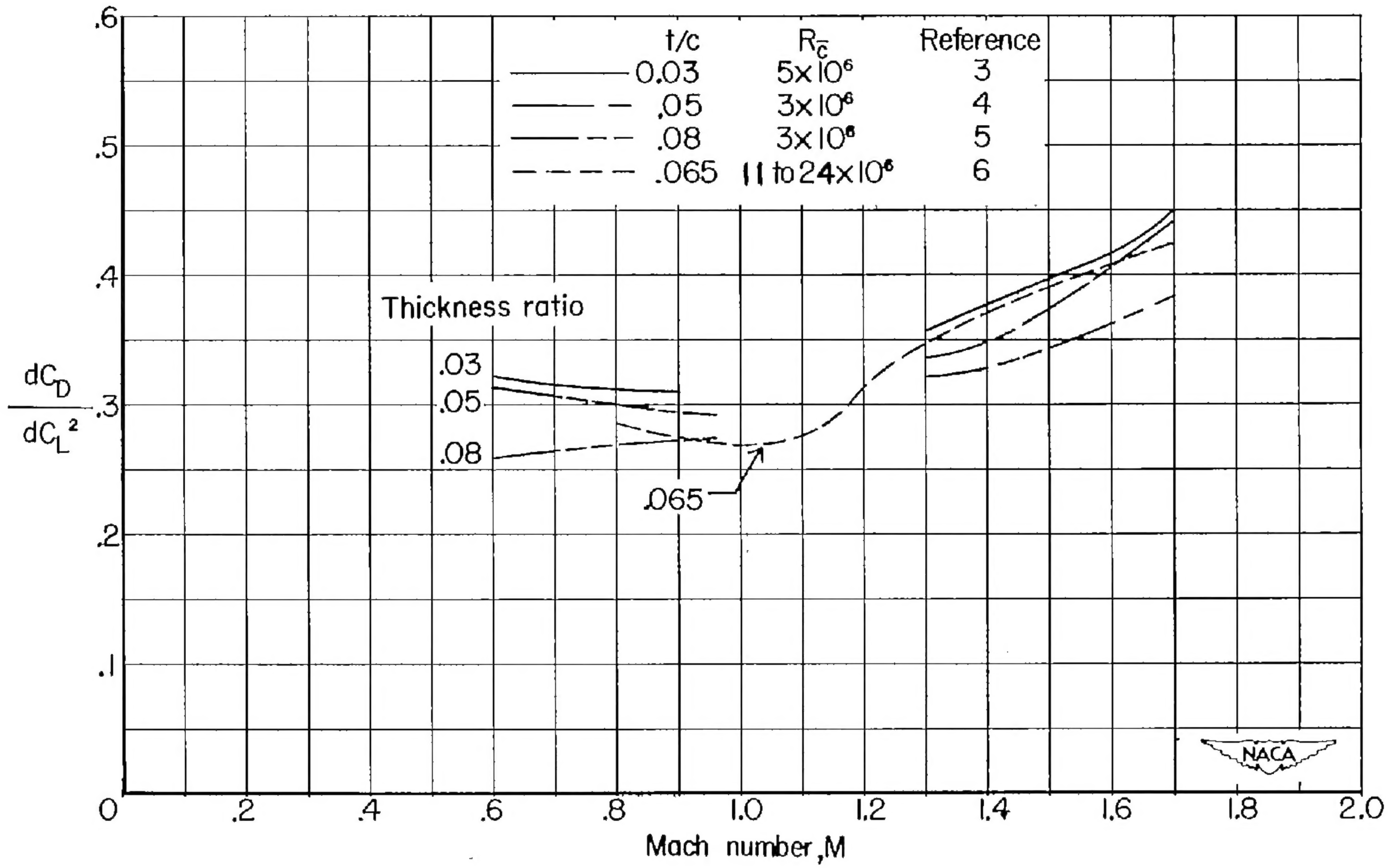


Figure 3.- Variation of drag-due-to-lift factor $\frac{dC_D}{dC_L^2}$ with Mach number for wing-body combinations having delta wings with thickness ratios from 3 to 8 percent chord. $A \approx 2.0$. $\left(\frac{dC_D}{dC_L^2}\right.$ averaged to $\left.C_L = 0.3.\right)$

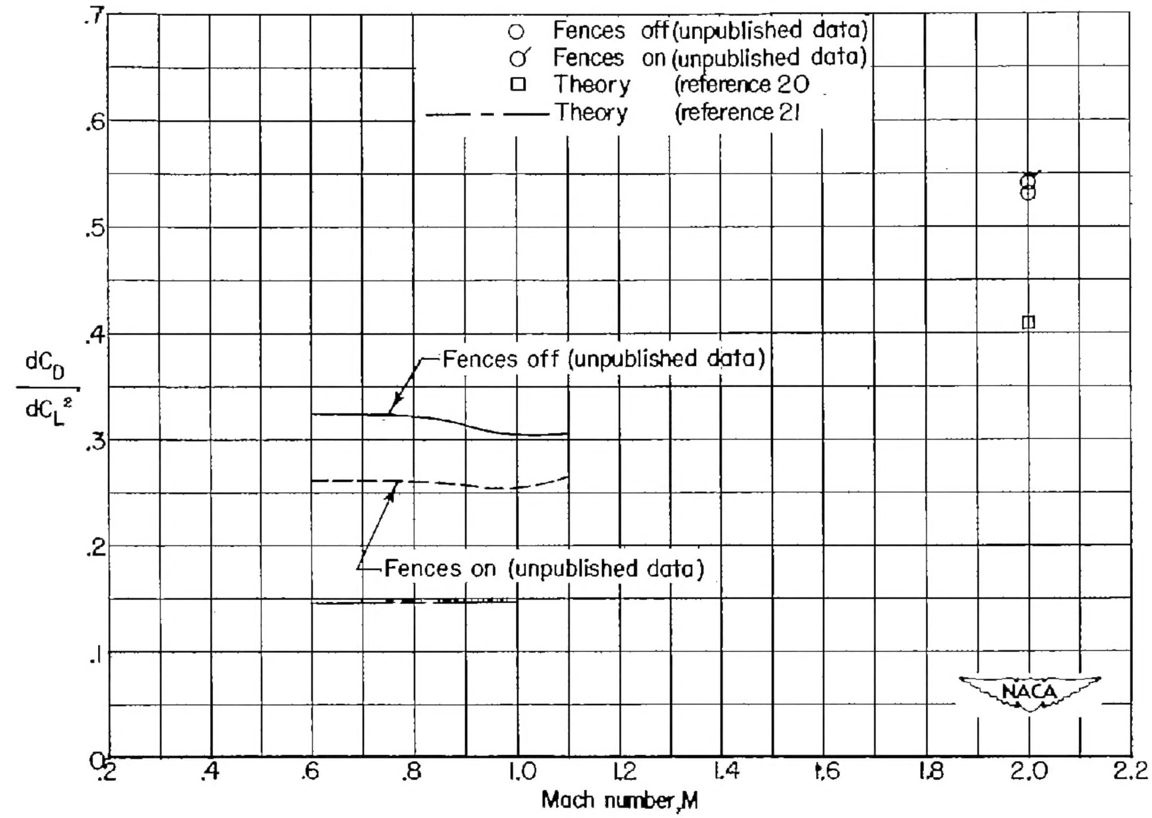


Figure 4.- Variation of drag-due-to-lift factor $\frac{dC_D}{dC_L^2}$ with Mach number for a wing-body combination having delta wings of aspect ratio 2.2 with and without chordwise fences. $R_{\bar{c}} \approx 4.5 \times 10^6$. $\left(\frac{dC_D}{dC_L^2}\right.$ averaged to $\left.C_L = 0.3.\right)$



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